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Validity of Analytical Predictions of Deck Wetness for an Offshore Supply Vessel in Following Waves

David W Taylor Naval Ship R & D Center, Bethesda, Md.

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DAVID W. TAYLOR NAVAL SHIP :ARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

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by

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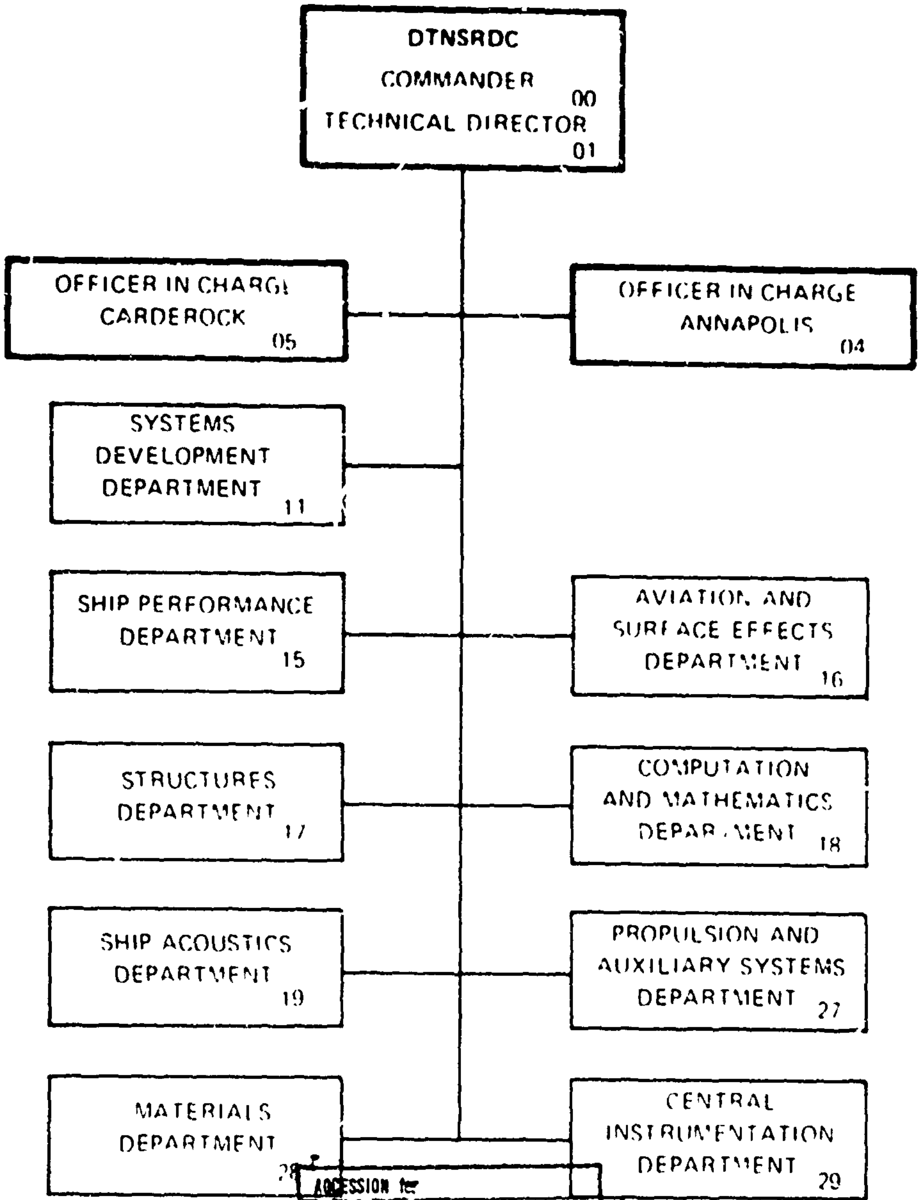

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NOTATION

F	Freeboard
F_G	Geometric freeboard
L	Ship length between perpendiculars
P_w	Probability of deck wetness
T_O	Modal wave period
r_A	Relative motion amplitude
$r_{1/3}$	Significant single amplitude of relative motion
Z_A	Heave amplitude
δF_1	Trim and sinkage correction to F_G
δF_2	Wave profile correction to F_G
$\epsilon_{Z\zeta}$	Heave-to-wave phase angle
$\epsilon_{\theta\zeta}$	Pitch-to-wave phase angle
ζ_A	Wave amplitude
$(\bar{\zeta}_w)_{1/3}$	Significant wave height
θ_A	Pitch amplitude
λ	Wavelength
ν_H	Maximum wave slope

ABSTRACT

The deck wetness characteristics of an offshore supply vessel in following waves are predicted analytically and compared with experimentally derived results. It is found that the analytical predictions are conservative given specified conditions. The conservatism of the analytical results is attributed primarily to the influence of dynamic swell-up and incident wave distortion on ship-to-wave relative motion.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The United States Coast Guard (USCG) has recently sponsored two investigations of offshore workboat deck wetness characteristics at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). The first of these investigations concerned a fishing vessel in head waves, and the results thereof are reported in references 1 and 2.* The second investigation, concerning an offshore supply vessel in following waves, is described hereinafter. All model quantities are given at the scale of the prototype unless otherwise specified.

VESSEL, OPERATING CONDITIONS, AND RESPONSES EVALUATED

A double-chine offshore supply vessel 52 metres (171 feet) in length was evaluated. The vessel characteristics supplied by the USCG are given in the

*References are listed on page 13.

second column of Table 1. Evaluation was limited to regular, following waves at vessel speeds of 5.0 and 12.5 knots.

Since only following waves were considered, emphasis was placed upon vertical plane responses: pitch, heave, and ship-to-wave relative motion. Relative motion was evaluated at the stern, at the forward and after quarter-points, and at the longitudinal center of buoyancy location. These responses were determined for various wavelengths up to five times the length of the vessel.

ANALYTICAL PROCEDURE AND RESULTS

The DTNSRDC Ship Motions and Sea Loads computer program, described in reference 3, was used to compute the pitch, heave, and associated phase angle characteristics of the subject vessel in following waves at speeds of 5.0 and 12.5 knots. The analytical model of hull geometry used for the computations is shown in Figure 1. Some of the characteristics of this analytical model are quantified in the third column of Table 1.

Results of the Ship Motions and Sea Loads computer program are presented in Figures 2 through 9 as solid lines. Phase angle results are given as lags with respect to maximum wave elevation at the longitudinal center of buoyancy location. The 12.5-knot curves have been faired with discontinuities at a wavelength to ship length ratio of 0.5 to indicate that encounter frequency goes to zero under this condition. (At 5.0 knots, encounter frequency goes to zero in waves of less than 0.1 ship length. This wavelength is shorter than considered, so the 5.0-knot curves do not show discontinuities.)

Relative motions were computed from the data presented in Figures 2 through 9 by taking the vector sum of heave, wave elevation, and pitch-induced displacements at the after perpendicular, the forward and after quarterpoints, and the longitudinal center of buoyancy location. (The longitudinal center of buoyancy was assumed to lie 1.48 metres (4.85 feet) aft of amidships in accordance with the results of the Ship Motions and Sea Loads computer program.) Relative motion results so-computed are shown as solid lines in Figures 10 through [illegible]. Discontinuities indicating zero encounter frequency are again shown in the 12.5-knot curves.

The analytical results just presented were obtained prior to conducting the supply vessel experiment. In view of the wave encounter frequencies associated with the conditions investigated (these frequencies are low and vary quite slowly for waves of ship length and longer), the results were thought to be viable. They were, accordingly, taken as a basis for designing the experiment.

EXPERIMENTAL PROCEDURE AND RESULTS

The USCG supplied a model identified as S-04 for the experiment. This model represented the prototype offshore supply vessel at a scale ratio of 17.47. The experimental facility, apparatus and methodology employed were generally as reported for the earlier experiment with the fishing vessel model (see Appendix A of reference 1). Here it should be noted that:

1. The model was ballasted to the prototype equivalent characteristics listed in the fourth column of Table 1.
2. The model was fitted with a solid bulwark extending around the stern and forward to the after quarterpoint. This bulwark was 1.07 metres (3.5 feet) high at the scale of the prototype.
3. While data was being collected, the model was self-propelled and free to move in all degrees of freedom. Course was maintained by an automatic rudder control system while speed was maintained by manual control of an electric motor which powered the model.
4. The measurements of primary concern were wave height, pitch, heave, and relative motions at the after perpendicular, the forward and after quarterpoints, and the longitudinal center of buoyancy (1.48 metres (4.85 feet) aft of amidships). Roll, surge, sway, yaw, carriage velocity and rudder angle were also measured.

In the context of items 1 and 4 above, ballasting to metacentric height and measurement of horizontal plane responses and rudder angle are not normal procedure for experiments in head or following waves. However, a prior experiment with model S-04, see reference 4, indicated that this model could become

unstable and capsize in extremely steep following waves. Though the experiment now under discussion was not intended to explore conditions so extreme as to lead to capsizing, it was thought that an experimental design which accommodated the possibility was desirable. Accordingly, ballasting to metacentric height and the extra measurements were included.

The basic experimental program consisted of runs in regular, following waves of the various lengths needed to define pitch, heave and relative motion transfer functions and the phase angles of pitch and heave with respect to the incident waves. For these runs, wave slope was decreased with increasing wavelength, i.e., from 3.5 ± 0.5 degrees in waves of one-half ship length to 1.0 ± 0.5 degrees in waves of five times ship length.

In waves of ship length and of twice ship length, wave steepness was varied to assess the linearity of the measured responses. Wave slopes on the order of nine degrees were reached during the linearity runs in waves of ship length at 5.0 knots, and a slope exceeding six degrees was attained in waves of the same length at 12.5 knots. In waves of twice ship length, wave slopes in excess of four degrees were attained at both speeds.

Calm water runs were made to determine the vessel's trim, sinkage, and wave profile characteristics at 5.0 and 12.5 knots.

All measured transfer function and phase angle data (including that from the linearity runs) are shown in Figures 2 through 17 as open circles. These data are fundamental mode results as obtained by Fourier analysis of the measured time histories. It can be noted that there is considerable scatter in the pitch and heave transfer function data for long waves at 5.0 knots (Figures 2 and 4), and in the relative motion transfer function data for all locations and both speeds in short waves (Figures 10 through 17).

The scatter in the relative motion transfer function data is not surprising in view of the fact that these transfer functions are maximized in short waves where phase angle variability is rapid (see Figures 3, 5, 7, and 9). On the other hand, the scatter of the 5.0-knot pitch and heave transfer function data in long waves is most unusual. The available data do not indicate that either pitch or heave exhibit consistent, nonlinear trends in long waves at 5.0 knots, so the scatter can only be attributed to some

type of instability under these conditions. An investigation of the auxiliary date collected did indicate that rolling motion at 5.0 knots was about 40 percent higher than that at 12.5 knots. However, the magnitudes involved were small at both speeds. In terms of time domain root mean square values, rolling motion at 5.0 knots was typically on the order of 0.3 degrees while that at 12.5 knots was 0.2 degrees.

Possible nonlinear trends were found to occur only for relative motion at 5.0 knots in waves of ship length. Supporting data are shown in Figure 18. The nonlinearity involved is mild, and is of the type (response increasing at a decreasing rate with wave amplitude) which causes the transfer function to decrease with increasing wave amplitude. (This situation contrasts that found in the earlier fishing vessel investigation reported in reference 1. The fishing vessel exhibited distinct nonlinearities with response increasing at an increasing rate with wave amplitude.)

Calm water data are presented in Table 2. The values tabulated are averages over three runs at 5.0 knots and two runs at 12.5 knots. The 5.0-knot results exhibited significant run-to-run variability. They should, accordingly, be taken simply as an indication that trim, sinkage, and wave profile are "small" at 5.0 knots.

To conclude this section, a few qualitative observations are in order. The model was observed to ship water only during the runs made in steep waves to investigate linearity. The wetness occurred in way of amidships (where there was no bulwark) rather than at the stern. Wave profile overtopping appeared to be the major causal phenomenon. Though instability has been hypothesized to be the cause of the scatter in the pitch and heave transfer function data at 5.0 knots in long waves, no instability was evident from observation of the experiment.

COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

Figures 2 through 17 provide the basic comparisons. Pitch is notably underpredicted in long waves at both speeds considered (Figures 4 and 8). Relative motion is rather consistently overpredicted. The only notable

exception to the overprediction of relative motion occurs in long waves at 5.0 knots for the longitudinal center of buoyancy location (Figure 12). Here the predictions are rather accurate.

To gain an understanding of the discrepancies between the analytical and experimental results for relative motion, the limitations of the analytical methodology employed must be considered. As previously noted, relative motions were computed by taking the vector sum of analytically-predicted heave, wave elevation, and pitch-induced displacements at the locations evaluated. This state-of-the-art procedure accounts only for what can be termed the kinematic component of relative motion. It neglects dynamic swell-up (reference 5) and incident wave distortion (reference 6). When, as in the present investigation, analytical predictions of pitch, heave, and the phase angles of these motions with respect to the incident waves are not extremely accurate, the magnitude of the nonkinematic components of relative motion is best evaluated by computing kinematic relative motion from measured pitch and heave data; and thence, comparing these results with measured relative motion. A comparison of this type was made using selected data from the supply vessel experiment. It was found that kinematic relative motion computed on the basis of measured pitch and heave data was on the order of that measured in long waves but significantly exceeded measured relative motion in short waves. In fact, the kinematic relative motion predictions based on measured pitch and heave data frequently exceeded the like predictions based on analytically determined pitch and heave characteristics. Figure 10 (after perpendicular relative motion at 5.0 knots) includes a sample comparison. The "hybrid" curve is faired from kinematic relative motion transfer functions computed on the basis of measured pitch and heave data.

The finding just discussed is of practical importance. Previous investigations of the nonkinematic components of relative motion in head waves, e.g., the fishing vessel investigation reported in reference 1, have generally indicated that these components tend to increase relative motion in short waves. Under such circumstances, predictions of relative motion statistics in irregular waves will be unrealistically low if they are based on kinematic relative motion transfer functions. In the present case, however, relative motion is decreased

by its nonkinematic components. Hence, analytical predictions of relative motion statistics for this case will be conservative, i.e., high. All other elements being equal, an overprediction of relative motion in irregular waves will produce a conservative or somewhat overpredicted deck wetness probability. This matter will be addressed in greater depth in the subsequent section.

DECK WETNESS PREDICTIONS

As noted in the preceding section, conservative predictions of relative motion statistics will yield conservative predictions of deck wetness if "all other elements are equal." Figures 10 through 17 clearly indicate that the analytical results for the supply vessel in following waves will yield conservative estimates of relative motion under linear superposition (reference 7). Further, the results already described indicate that linear superposition is valid for relative motion at the 12.5-knot speed; and will produce additional conservatism at 5.0 knots. Hence, the matters to be addressed here are the degree of conservatism involved and the influence of elements other than relative motion on the prediction of deck wetness.

The probability of occurrence of deck wetness, say P_W, can, for a specified location, be written as

$$P_W = e^{-2(F/r_{1/3})^2} \qquad [1]$$

where F is the freeboard at the specified location and $r_{1/3}$ is the significant single amplitude of relative motion at that location (reference 8). So, if identical values are assumed for F, a conservative prediction of $r_{1/3}$ will evidently lead to a conservative prediction of P_W. In a purely analytical approach to calculating P_W, F is measured from the hydrostatic waterline to the weather deck edge or to the top of the bulwark. This measurement may be identified as "geometric freeboard" and symbolized by F_G. If experimental data are available, F_G can be corrected to account for the influence of trim and sinkage and of the wave profile, i.e.,

$$F = F_G \pm \delta F_1 \pm \delta F_2 \qquad [2]$$

where δF_1 is a correction for trim and sinkage and δF_2 is a correction for the wave profile. If these corrections are introduced in the experimental case, a conservative analytical prediction of $r_{1/3}$ does not guarantee a conservative analytical prediction of P_w.

To explore the matters just discussed quantitatively for the supply vessel, relative motion and deck wetness calculations were made for the after perpendicular at 12.5 knots. This case was selected because it involved relatively large freeboard corrections (see Table 2), and was representative of the general nature of the discrepancies between the analytical and experimental relative motion transfer functions. The calculations are described below.

Initially, analytical and experimental transfer functions were derived from Figure 14. The analytical transfer function was arbitrarily faired through the zero encounter frequency region and into $r_A/\zeta_A = 1$ at $\lambda/L = 0$. The experimental transfer function was faired through the approximate mode of the data points and into $r_A/\zeta_A = 1$ at $\lambda/L = 0$. The resultant transfer functions are shown in Figure 19.

From inspection of Figure 19, it is evident that relative motion will be maximized in wave spectra with modal wavelengths equal to or less than the length of the vessel (for a given unimodal wave spectral family and an arbitrary wave height statistic) Since the vessel is only 52 metres (171 feet) long, it seemed advisable to investigate the realism of these critical conditions before proceeding with the computations. This was accomplished using data from the Hogben and Lumb Wave Atlas (reference 9) Area 15 of this atlas lies in the Gulf of Mexico: a reasonable operational area for an offshore supply vessel. Accordingly, the observed wave statistics for this area (all seasons and all directions) were converted to significant wave height and modal wave period statistics using the calibrations given in reference 10; and taken as a basis for the assessment.

The results showed that nearly 90 percent of the wave systems occurring in the area investigated had modal lengths of 53 metres (175 feet) or less. Significant wave heights associated with these modal wavelengths were found to exceed 4 metres (13 feet) only rarely. However, significant heights to 7 metres

(23 feet) occurred in slightly longer waves. In view of these circumstances, focusing the calculations on wave spectra with short modal wavelengths appeared very reasonable.

Bretschneider wave spectra, reference 11, with unit significant wave heights and varying modal wave periods were used for the computations. Integrations were performed numerically over a range which accounted for essentially all of the wave energy present for modal periods up to eight seconds and involved a loss of only four percent at the highest modal periods evaluated. The resulting values of significant single amplitude of relative motion per unit significant wave height, $r_{1/3}/(\tilde{\zeta}_w)_{1/3}$, are presented in Figure 20 as a function of modal wave period, T_o. This figure shows that the values of $r_{1/3}/(\tilde{\zeta}_w)_{1/3}$ computed on the basis of the analytical transfer function from Figure 19 usually exceed those computed on the basis of the experimental transfer function from Figure 19 by about 0.1 (20 to 30 percent). For very low values of T_o, the analytical $r_{1/3}/(\tilde{\zeta}_w)_{1/3}$ drops below the experimental. However, the heights associated waves of such low modal periods are too small to be of practical concern.

Dimensional values of $r_{1/3}$ for use in computing the probability of occurrence of deck wetness, P_w in equation [1], can be obtained from Figure 20 for arbitrary values of $(\tilde{\zeta}_w)_{1/3}$. To illustrate, consider $T_o = 7.26$ seconds: the modal period corresponding to a modal wavelength equal to the length of the supply vessel under investigation. Then, from Figure 20, $r_{1/3}/(\tilde{\zeta}_w)_{1/3} = 0.411$ in the analytical case and $r_{1/3}/(\tilde{\zeta}_w)_{1/3} = 0.304$ in the experimental case. Multiplying these ratios by an arbitrary $(\tilde{\zeta}_w)_{1/3}$ of 4.0 metres (13 feet) gives $r_{1/3} = 1.64$ metres (5.4 feet) in the analytical case and $r_{1/3} = 1.22$ metres (4.0 feet) in the experimental case. Taking 1.58 metres (5.2 feet) as a reasonable value of freeboard to the top of the bulwark for F in equation [1], it is thence found that P_w equals 0.156 in the analytical case and 0.035 in the experimental case.

Figure 21 summarizes a series of computations of the type just described. The notation of equation [2] and data from Table 2 are used to define F with $F_G = 1.58$ metres (5.2 feet) as in the example above. For the most direct comparison, i.e., with equal freeboards, Figure 21 shows that the analytically

predicted probabilities of deck wetness exceed those based on experimental data by a factor of two or more for significant wave heights up to 6.0 metres (19.7 feet). The overprediction decreases to about 40 percent at 8.0 metres (26.2 feet). When freeboard is corrected for trim and sinkage (a decrease in this case) on the experimental side, the experimental probabilities are typically about 0.05 less than the analytical predictions. A further decrease in experimental freeboard due to wave profile raises the experimental probabilities to values marginally higher than the analytical predictions.

The foregoing results clearly indicate that experimentally-determined freeboard corrections can significantly modify the correlation between analytical and experimental predictions of the probability of deck wetness. In the particular case investigated, these corrections resulted in improved correlation; but this fortunate result cannot be expected to occur universally.

It is also relevant to note that using calm water data for the freeboard corrections, while it appears to be the best available procedure at the current state-of-the-art, may be inaccurate. This is particularly true in the case of the wave profile correction. It seems very likely that the incident and dynamic swell-up wave systems modify the calm water wave profile. Further, it can be hypothesized that wetness due to wave profile overtopping only is less severe than that associated with other causal phenomena.

CONCLUSIONS

The primary conclusion to be drawn from the foregoing material is that conservative predictions of deck wetness for the vessel and conditions investigated can be computed using state-of-the-art analytical procedures given that the same freeboard is assumed for both the analytical and experimental cases. Three cautionary notes are in order with respect to this conclusion:

1. Consideration of experimentally determined freeboard corrections for trim, sinkage, and wave profile can modify the degree of conservatism associated with the analytical results or, in extreme cases, make the analytical results nonconservative.

2. Since prior experiments with the vessel evaluated here (reference 4) indicate that instability and capsizing can occur in extremely steep waves, wetness predictions in extremely severe seas should be interpreted cautiously.

3. In view of the empirical nature of the results obtained here, extrapolation to significantly different hull forms and/or operating conditions should be avoided.

An important secondary conclusion is that dynamic swell-up and incident wave distortion decrease relative motion for the vessel and conditions investigated. This finding reverses that from previous investigations of other vessels in head waves, e.g., reference 1; and is the primary cause of the conservatism of the analytical results obtained. If this phenomenon can be shown to hold in general for following waves, the third restriction in the foregoing list can be relaxed considerably.

RECOMMENDATION

Both the offshore supply vessel experiment described here and the earlier experiment with the fishing vessel (reference 1) have indicated that the most common cause of deck wetness is water shipped in way of amidships. Offshore workboats frequently employ a raised fo'c'sle deck and sometimes a raised poop deck as well. These features, in combination with the relatively low amplitudes of relative motion in following waves, appear to offer an effective deterrent to shipping water over the bow or over the stern. On the other hand, such vessels almost invariably have extremely low freeboards in way of amidships. In head and/or following waves, the low freeboard amidships is to a degree offset by the fact that relative motion is smaller in way of amidships than at the ends of the vessel (since the contribution of pitch is small or nil in way of amidships). Nonetheless, the experimental evidence shows the midship region to be critical even in head and following waves. The fishing vessel investigated was so extreme in this respect that water was shipped in way of amidships even in calm water at the higher speeds investigated.

Though casualty statistics identify following waves as a major cause of instability in offshore workboats, the real environment will rarely produce

a purely following wave condition. Even if the predominant wave direction is from astern, there is very likely to be significant wave energy from other directions. This additional wave energy will induce rolling motion; and the effects thereof on a vessel which experiences deck wetness amidships even in head or following waves could be dramatic. The rolling motion will produce an additional relative motion component at the deck edge. This could cause the volume of water shipped to increase significantly. Both the increased volume and the influence of the more complex absolute motions of the vessel on the water on deck should increase the likelihood of instability developing.

In view of the foregoing considerations, it is recommended that attention be directed to assessing the deck wetness characteristics of offshore workboats in long-crested, unidirectional seas at oblique relative headings and/or in short-crested, multidirectional seas. An investigation along these lines would require a moderate developmental effort since very little work has been done on relative motion and related phenomena for other than long-crested head seas. But, unless there are errors in the logic presented here, the need for such an investigation is inescapable.

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TABLE 1 - CHARACTERISTICS OF THE VESSEL EVALUATED

Vessel Characteristic (units)	USCG Specification	Analytical Model (Input and output data)	Experimental Model (measured data)
Length Between Perpendiculars (m/ft)	---	51.97/170.5	---
Beam Amidships (m/ft)	---	11.70/38.4	---
Draft Amidships (m/ft)	3.69/12.11	3.69/12.1	3.69 $\pm$ 0.12/12.1 $\pm$ 0.4
Trim Down by Stern (m/ft)	0.36/1.19	0.37/1.2	0.37 $\pm$ 0.12/1.2 $\pm$ 0.4
Displacement in Salt Water (tonnes/long tons)	1531/1507	1533/1509	1572/1547
Longitudinal Center of Buoyancy: Distance Aft of Amidships (m/ft)	---	1.48/4.85	---
Longitudinal Radius of Gyradius (m/ft)	Approximately Length/4	12.99/42.63	13.2/43.3
Metacentric Height (m/ft)	---	2.37/7.79	2.37/7.79

TABLE 2 - CALM WATER DATA

Speed (knots)	Sinkage[1] (metres)	Trim[2] (degrees)	Wave Profile[3] (metres) AP	AGP	LCB	FQP
5.0	-0.094	0.06	-0.040	-0.040	-0.034	-0.076
12.5	-0.256	0.15	0.107	-0.433	0.073	-0.110

1 positive up

2 positive bow-up

3 positive wave elevation above running waterline

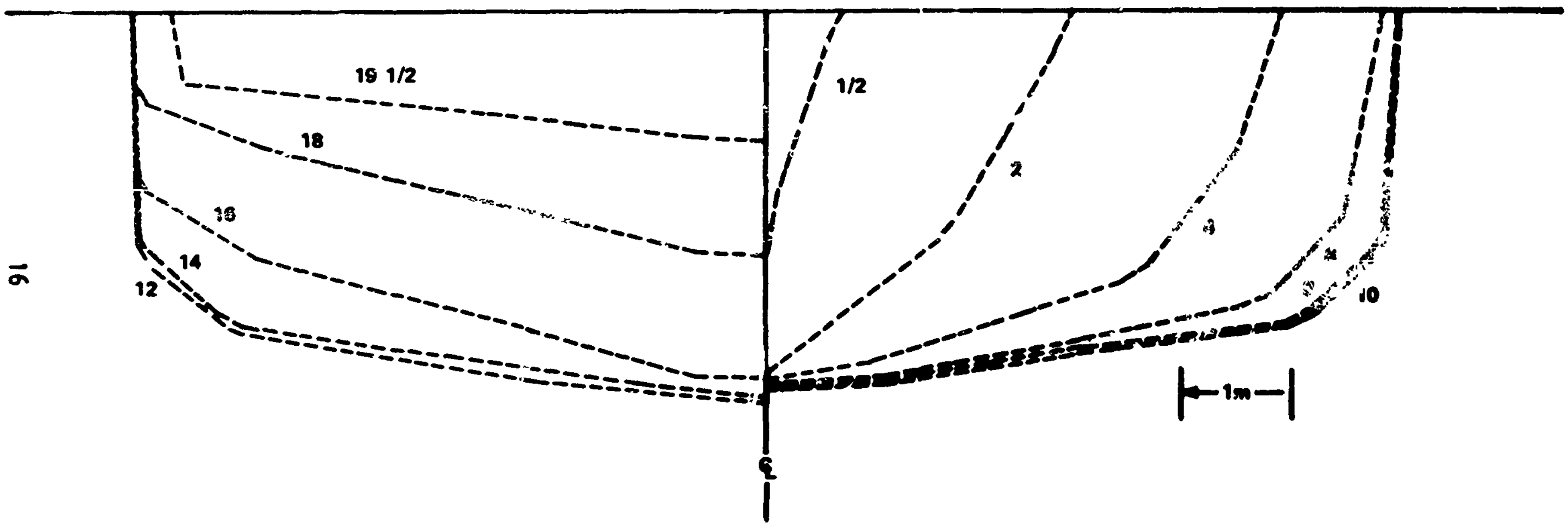
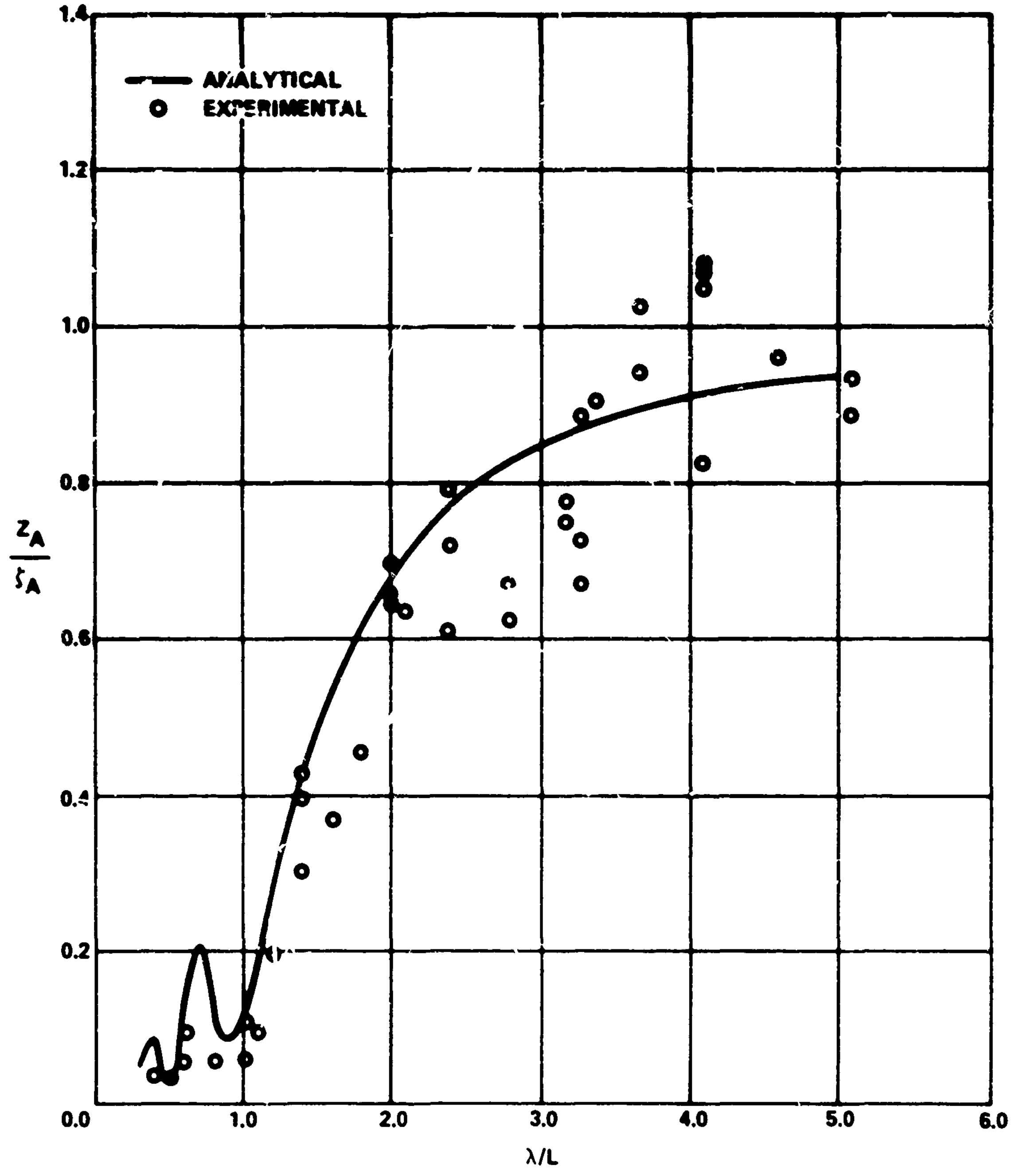
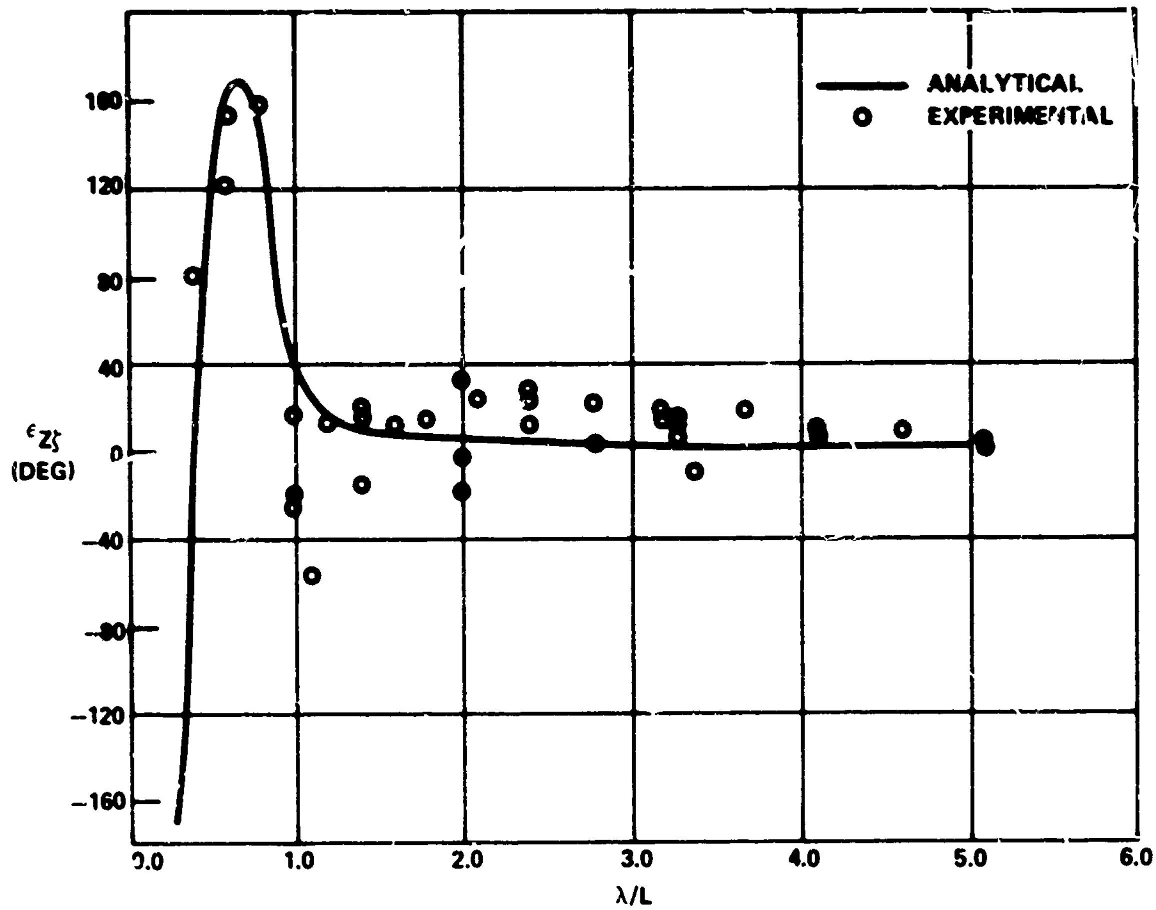


Figure 1 – Analytical Model of Hull Geometry



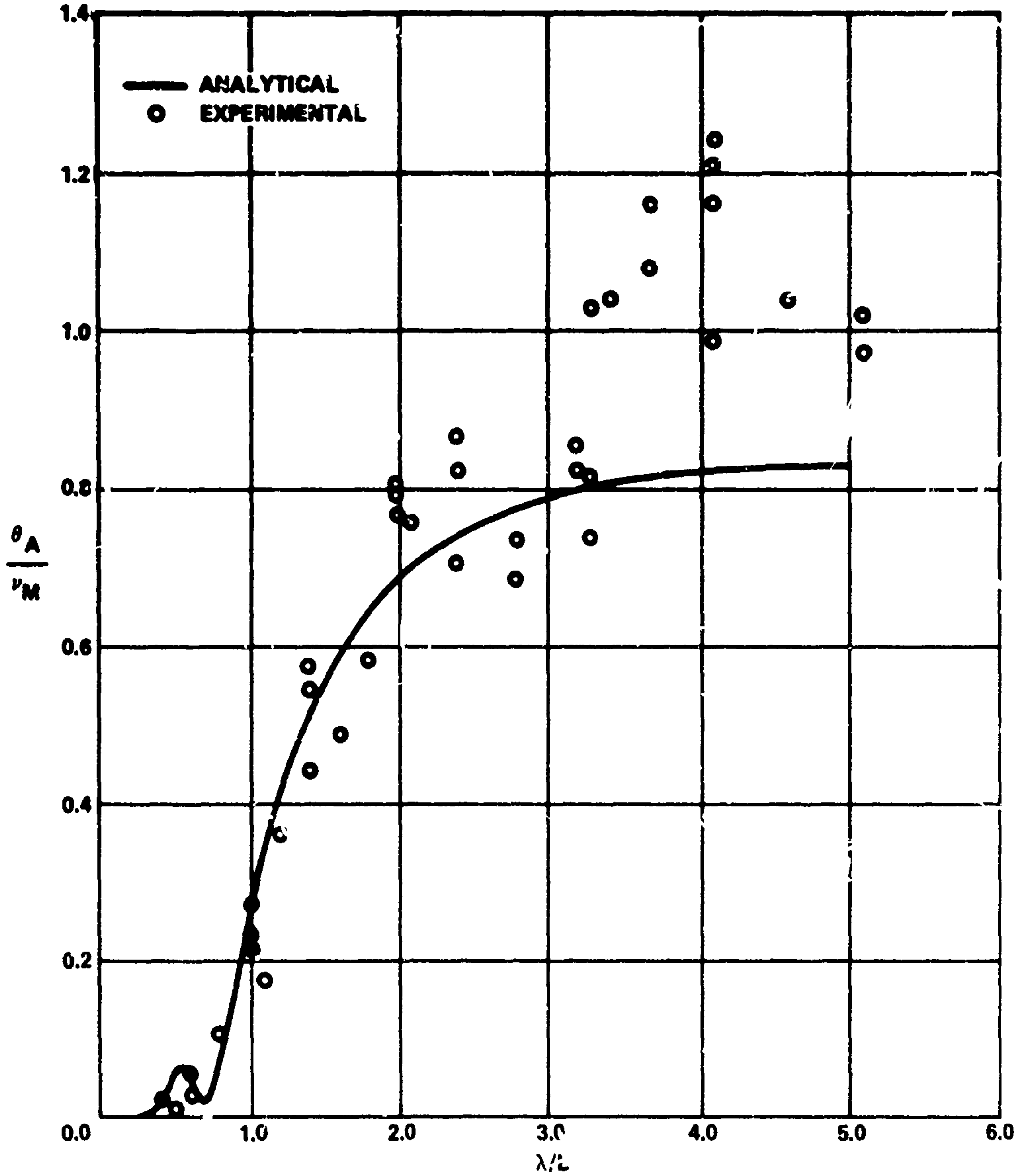
Heave Transfer Function at 5.0 Knots

Figure 2



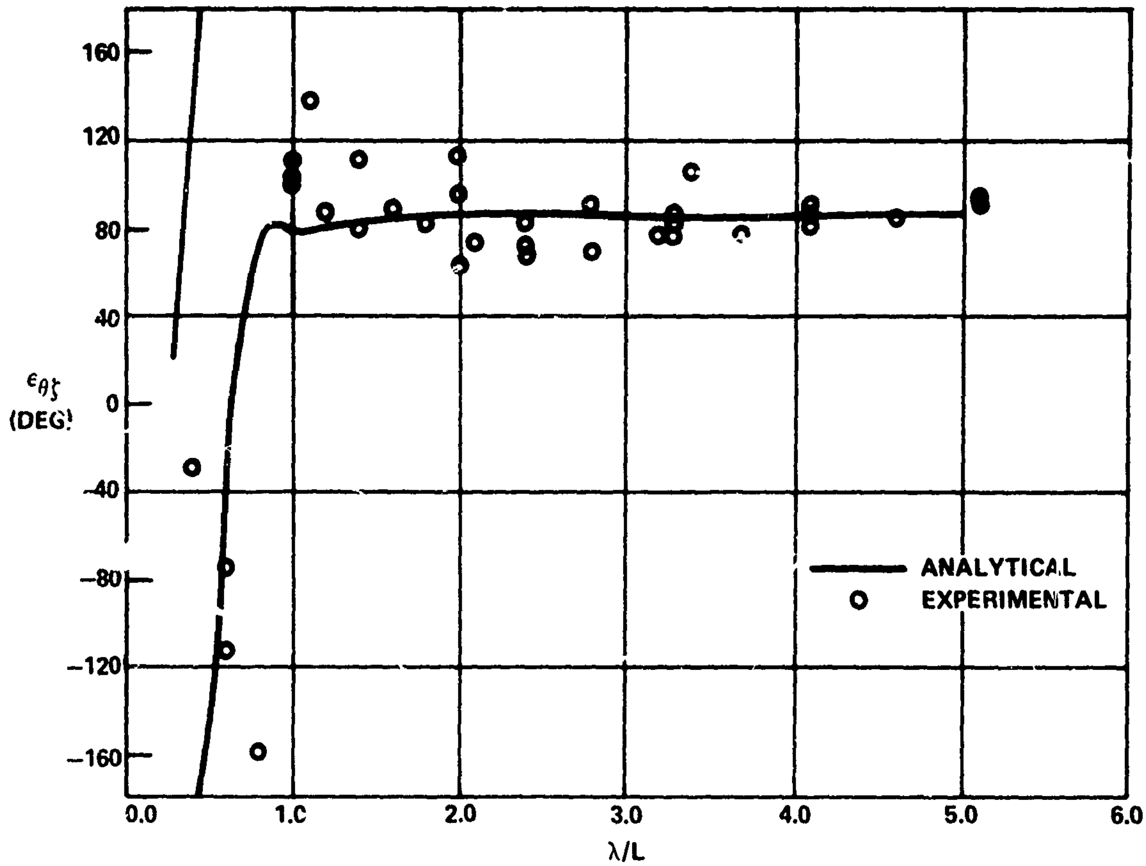
Heave Phase Angle at 5.0 Knots

Figure 3



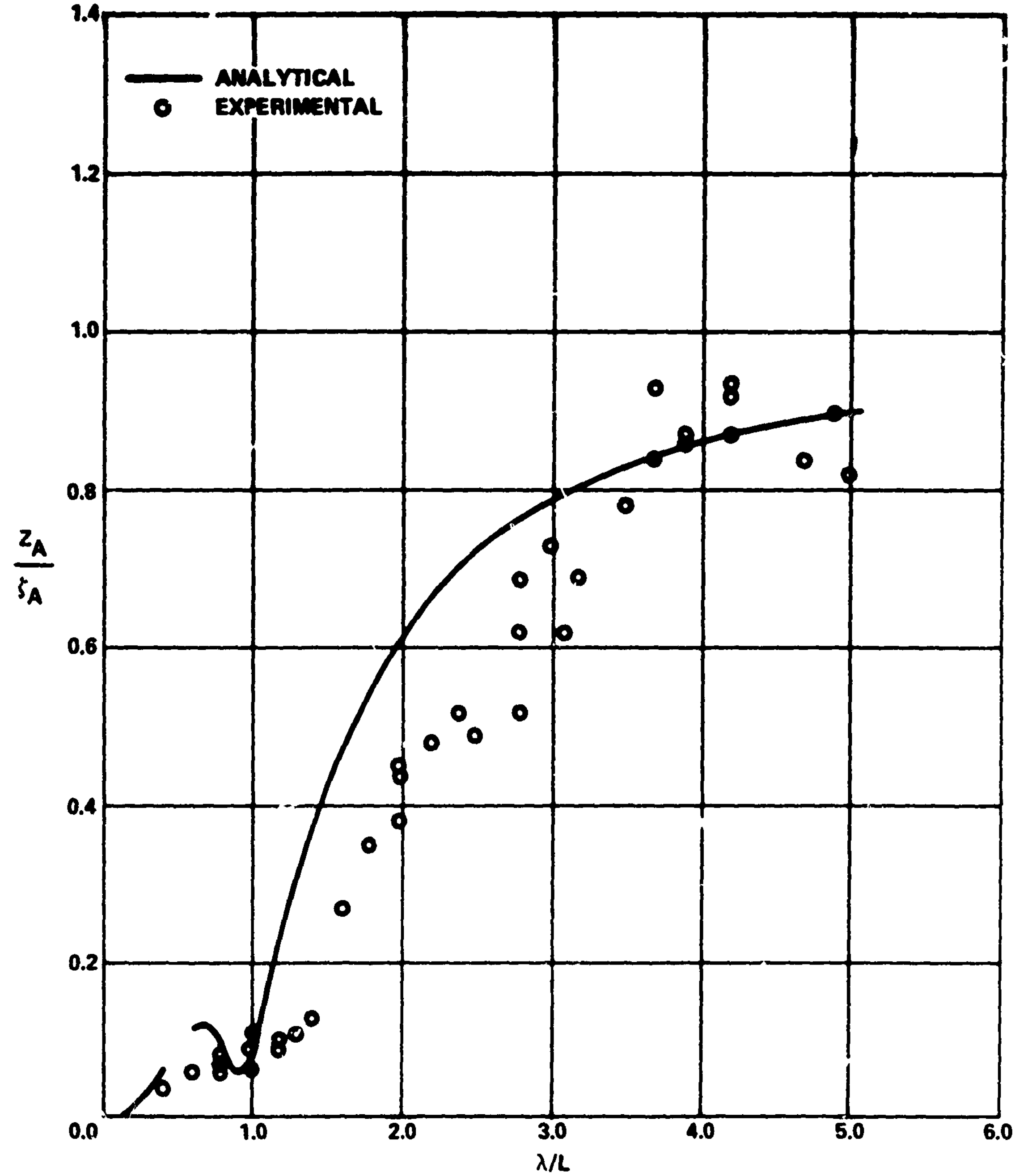
Pitch Transfer Function at 5.0 Knots

Figure 4



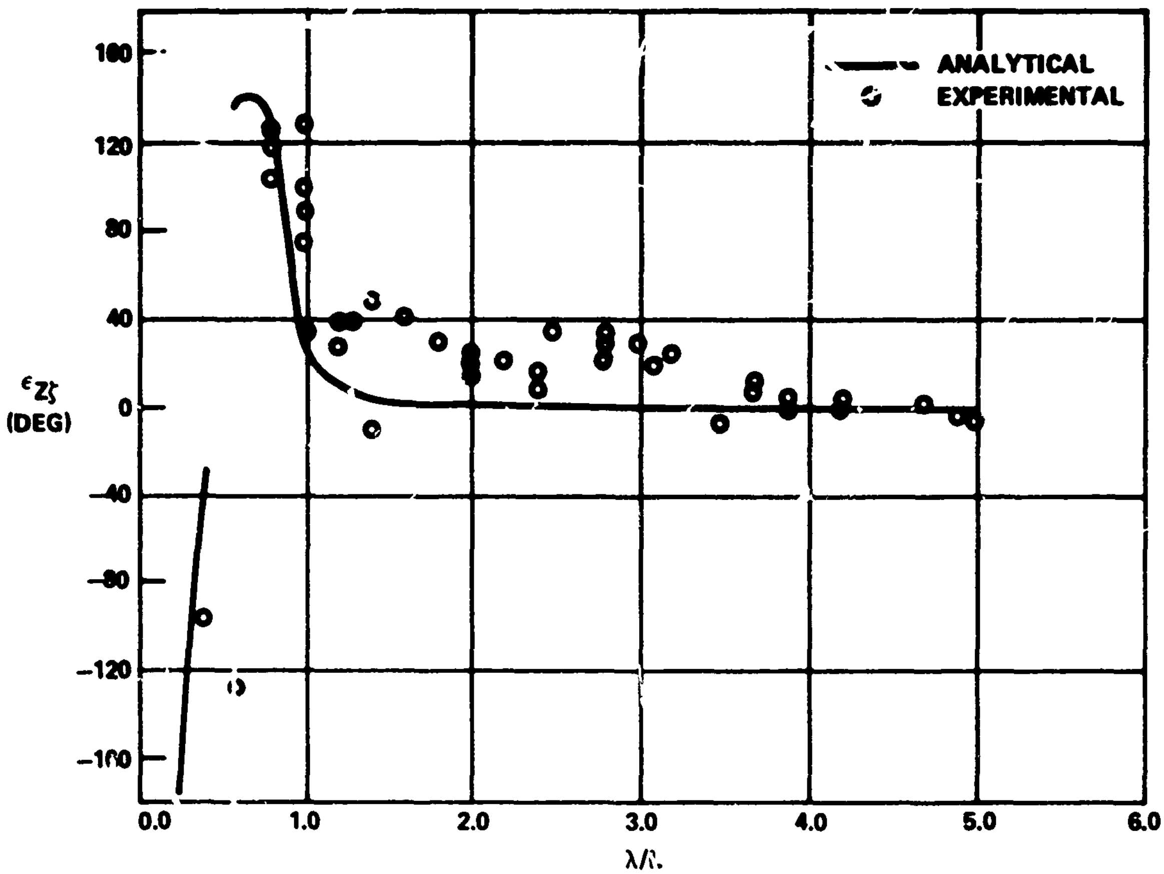
Pitch Phase Angle at 5.0 Knots

Figure 5



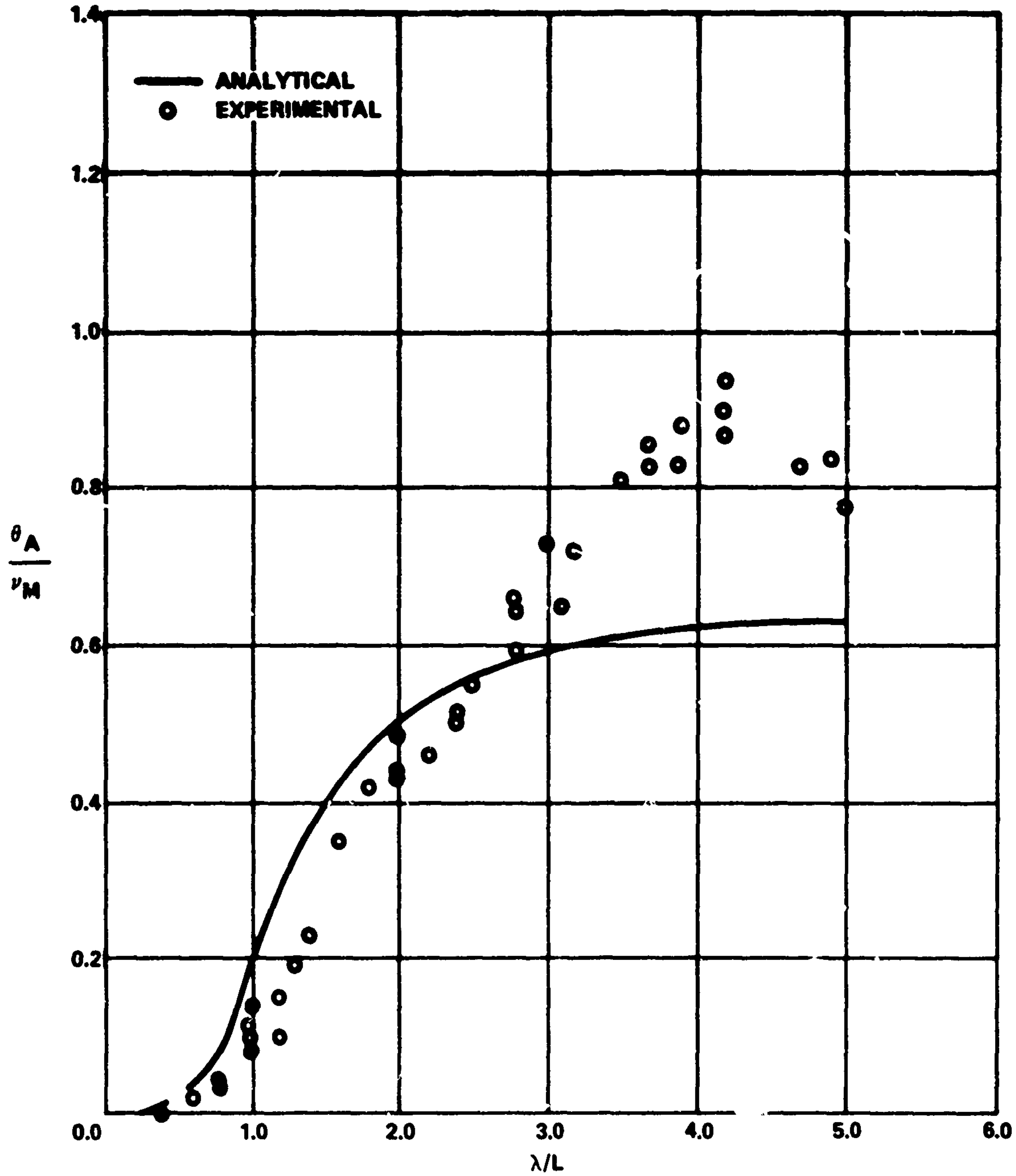
Heave Transfer at 12.5 Knots

Figure 6



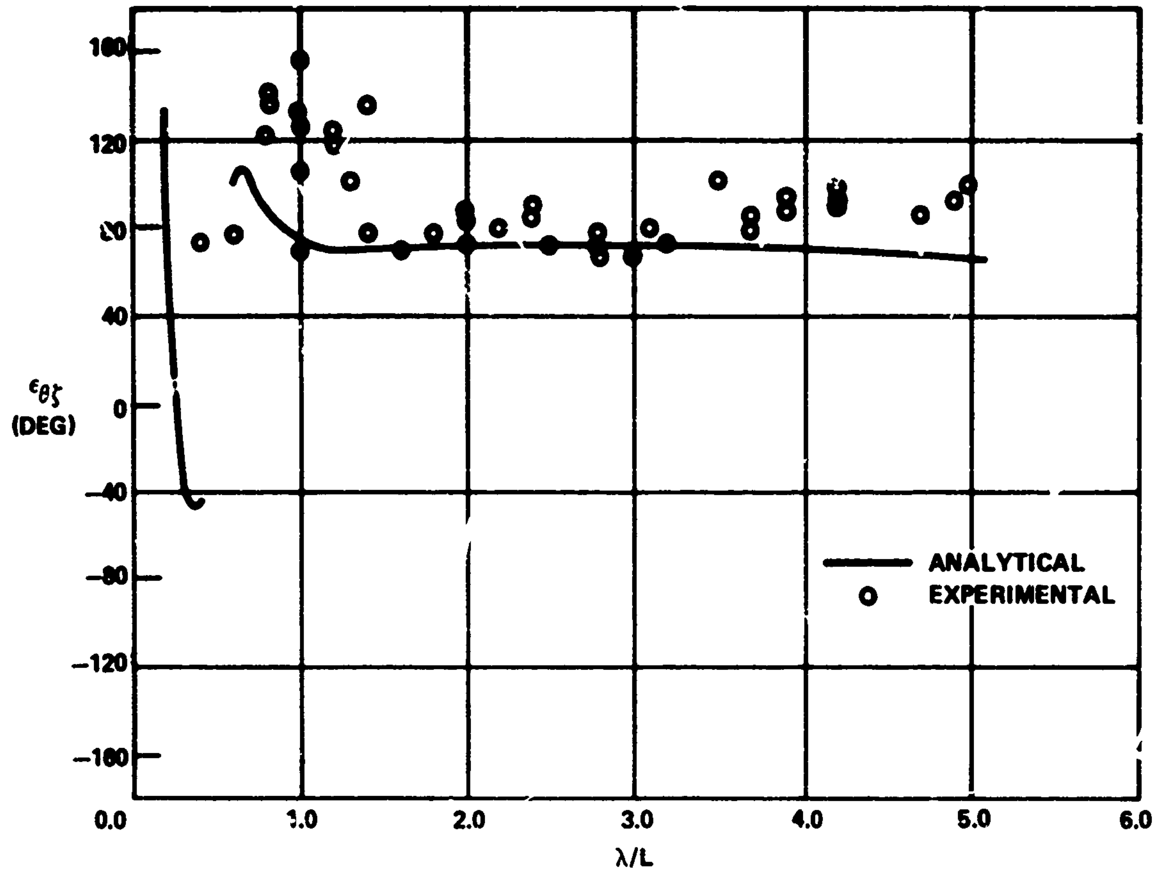
Heave Phase Angle at 12.5 Knots

Figure 7



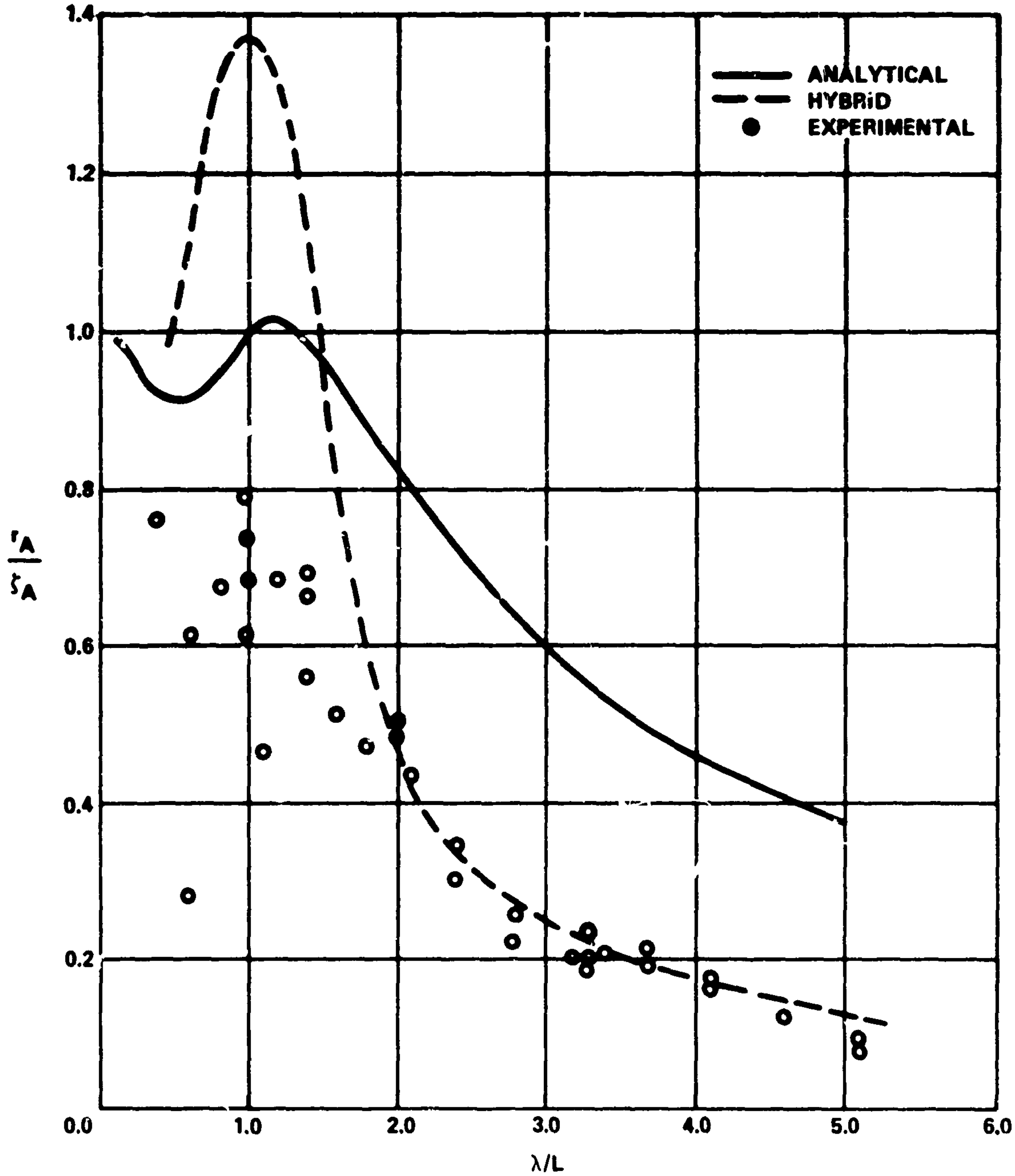
Pitch Transfer Function at 12.5 Knots

Figure 8



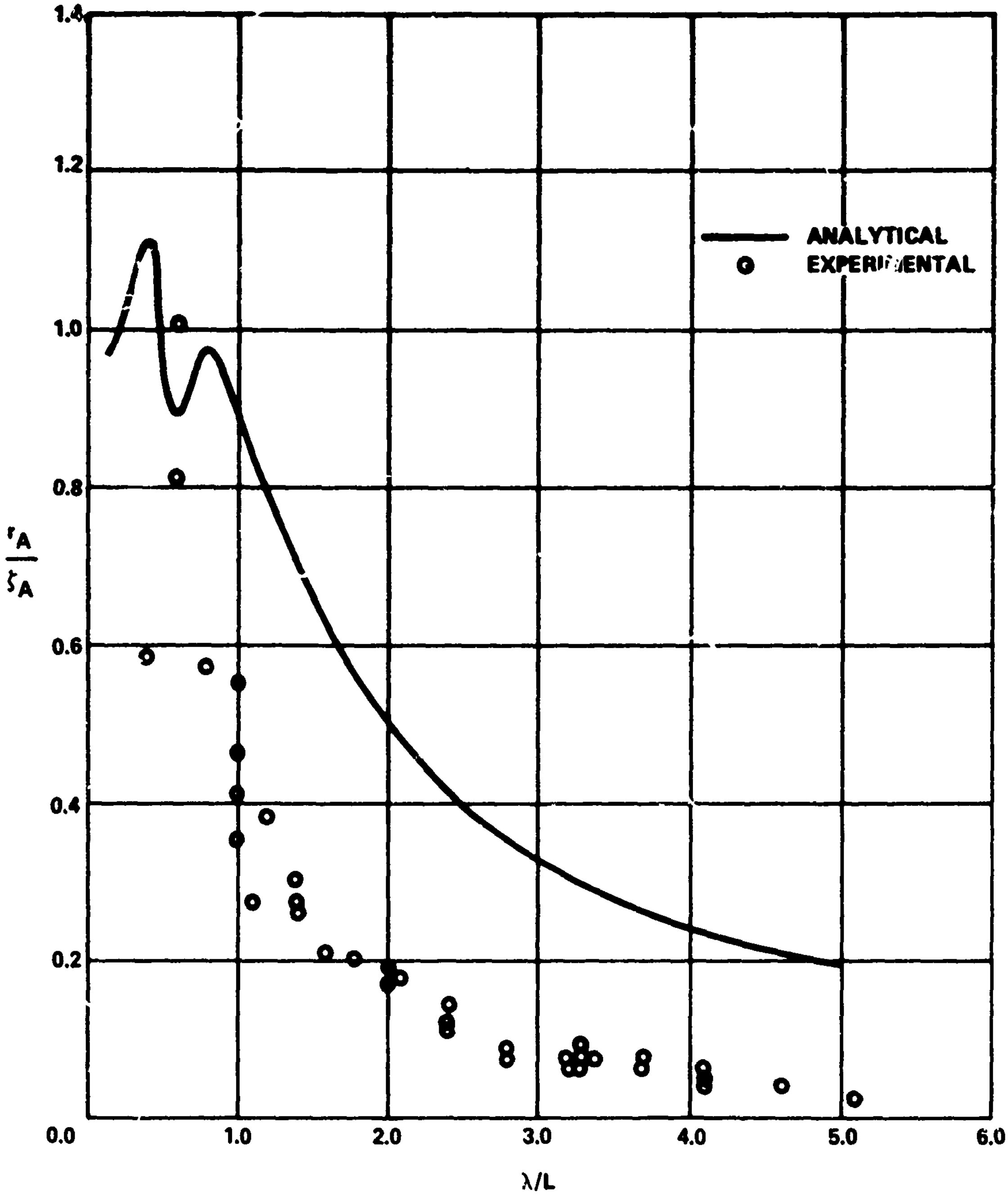
Pitch Phase Angle at 12.5 Knots

Figure 9



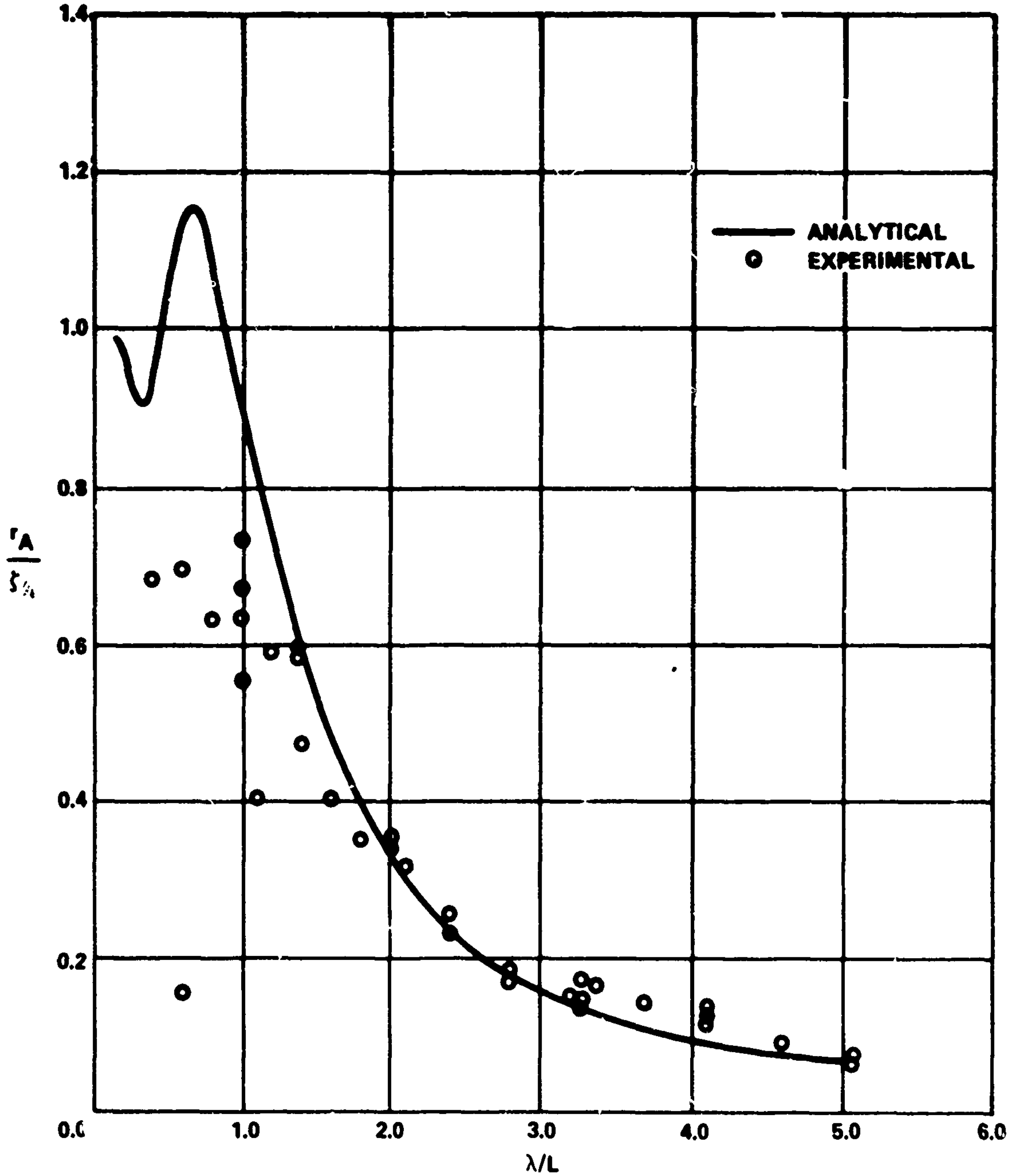
Relative Motion Transfer Function at After Perpendicular and 5.0 Knots

Figure 10



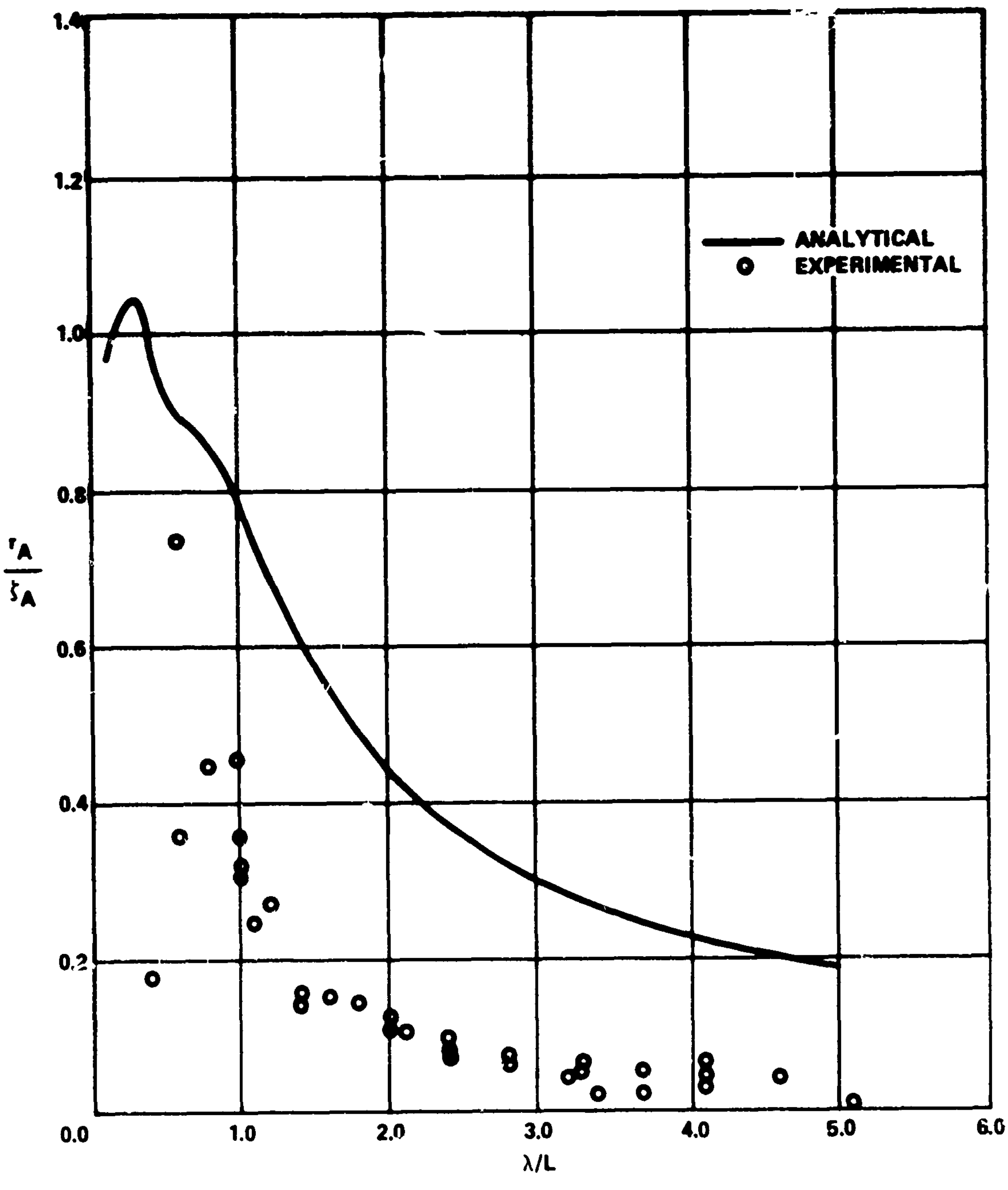
Relative Motion Transfer Function at After Quarter Point and 5.0 Knots

Figure 11



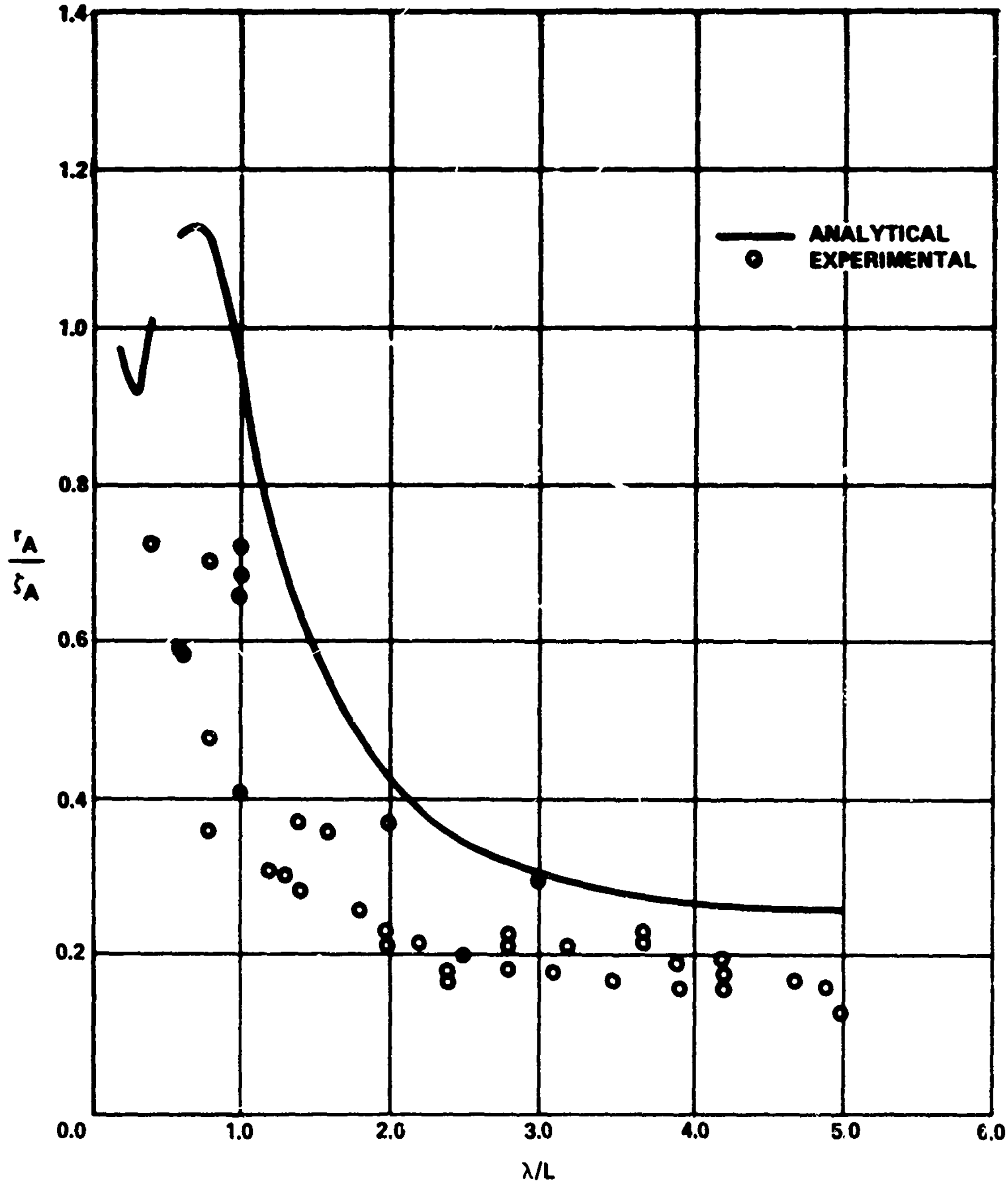
Relative Motion Transfer Function at Longitudinal Center of Buoyancy and 5.0 Knots

Figure 12



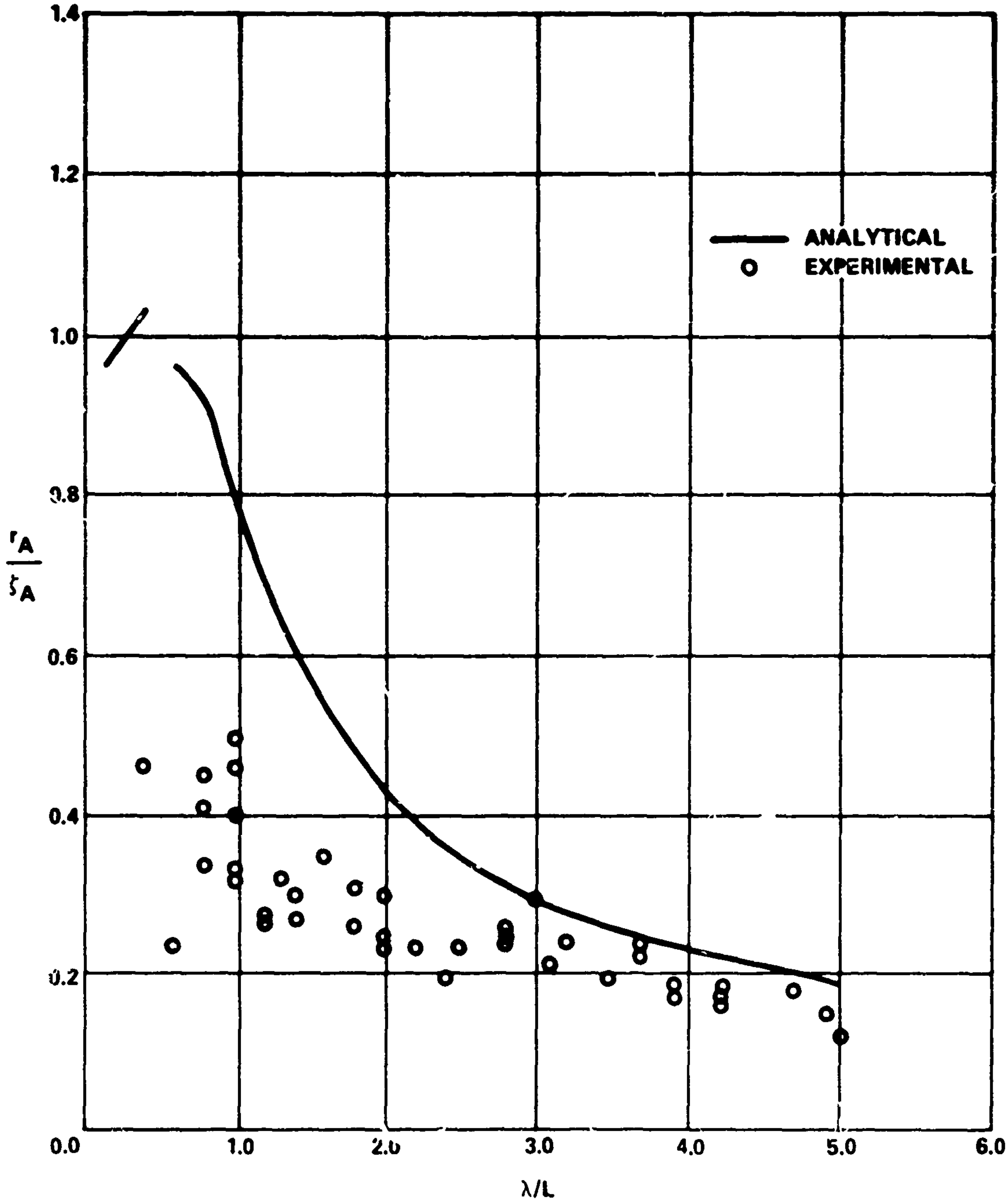
Relative Motion Transfer Function at Forward Quarter Point and 5.0 Knots

Figure 13



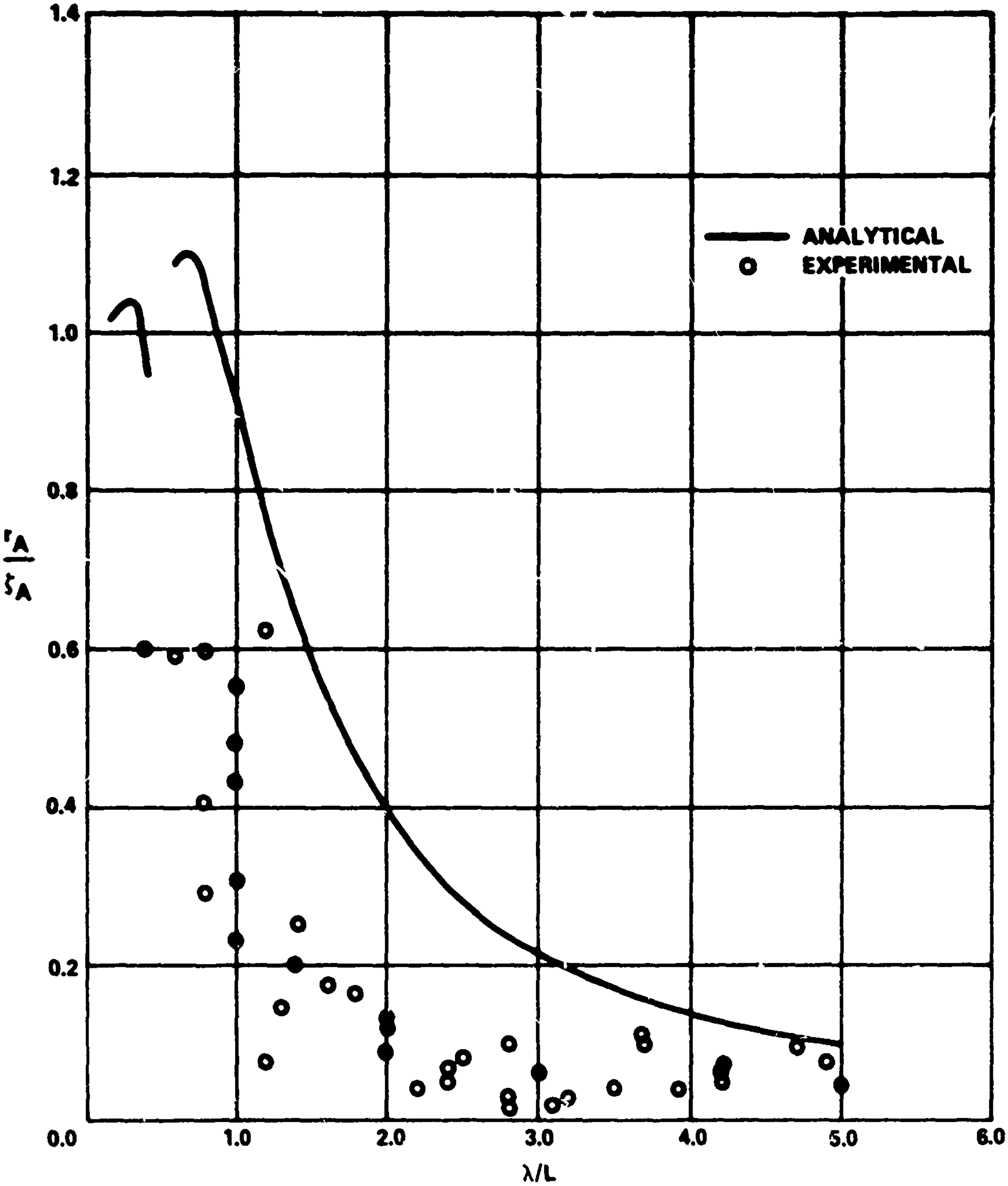
Relative Motion Transfer Function at After Perpendicular and 12.5 Knots

Figure 14



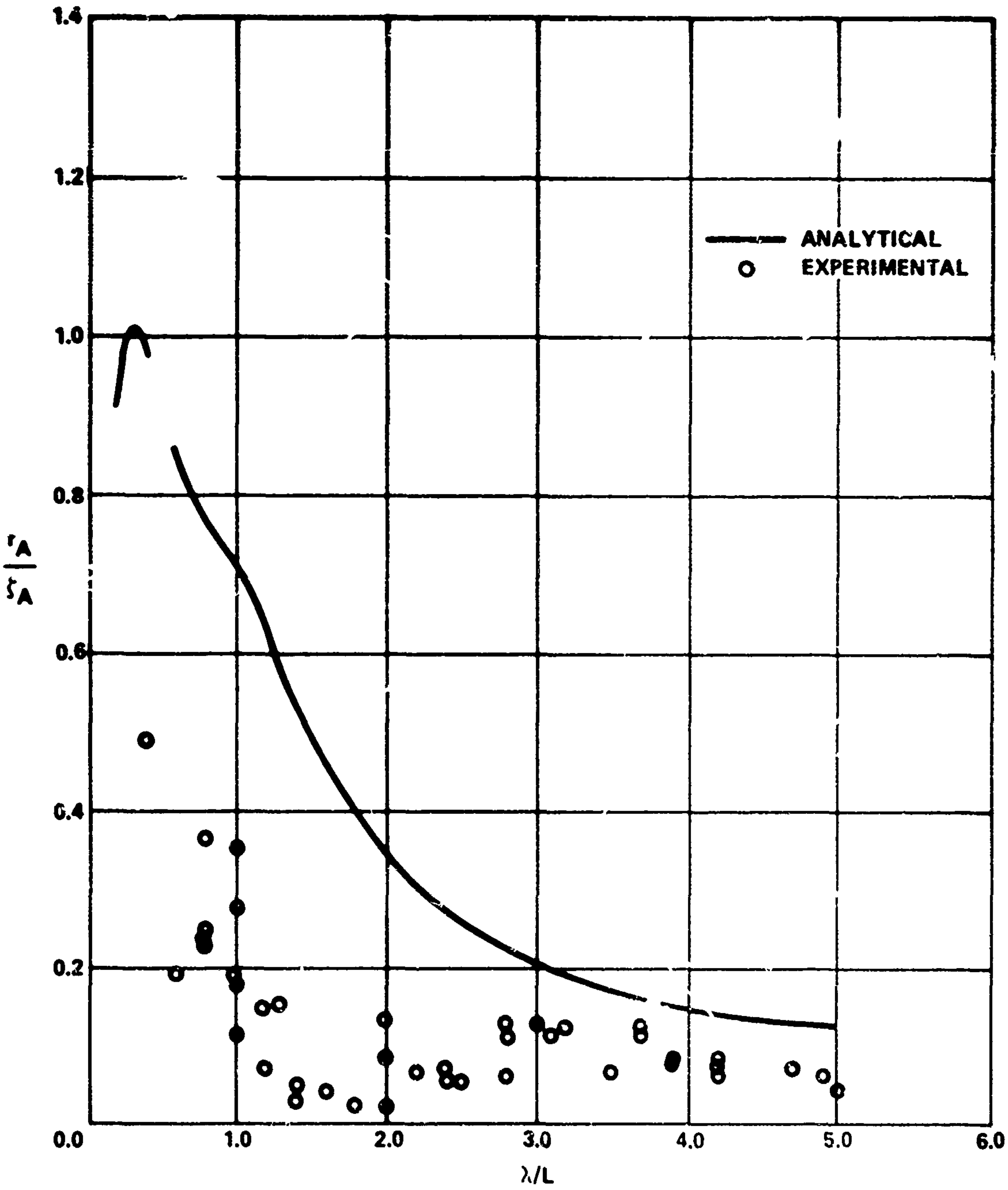
Relative Motion Transfer Function at After Quarter Point and 12.5 Knots

Figure 15



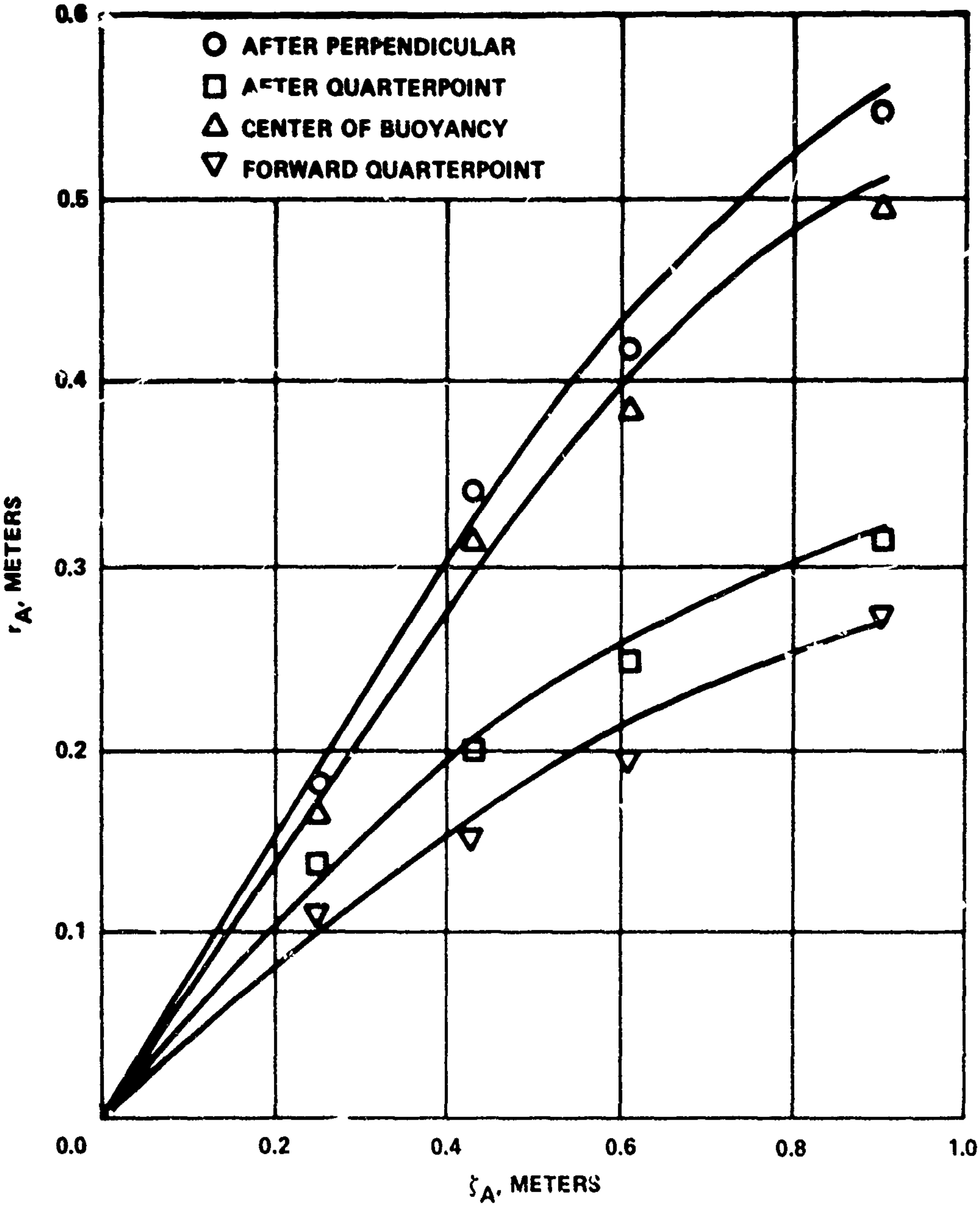
Relative Motion Transfer Function at Longitudinal Center of Buoyancy and 12.5 Knots

Figure 16



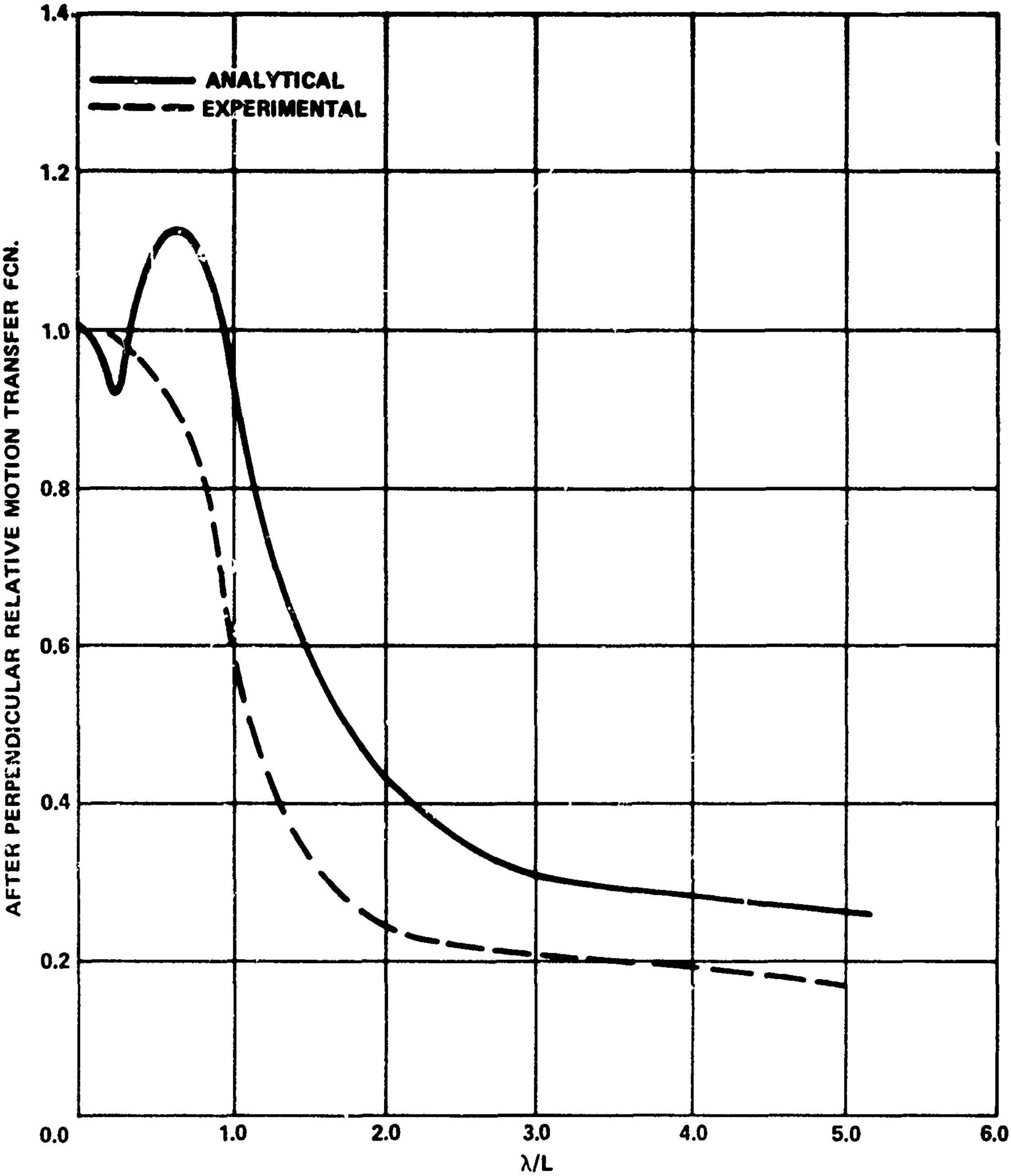
Relative Motion Transfer Function at Forward Quarter Point and 12.5 Knots

Figure 17



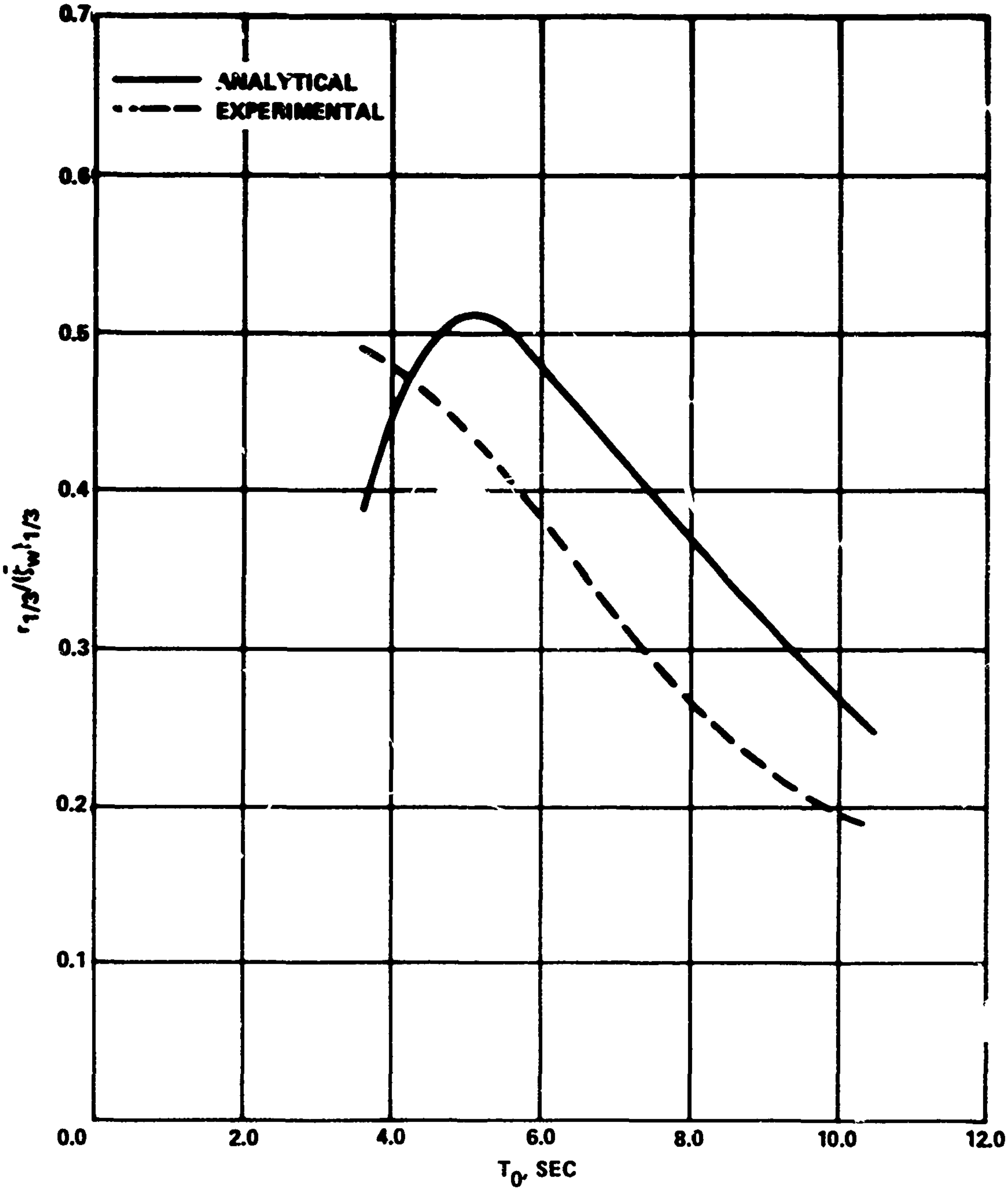
Relative Motion Amplitude versus Wave Amplitude at 5.0 Knots in Waves of Ship Length

Figure 18



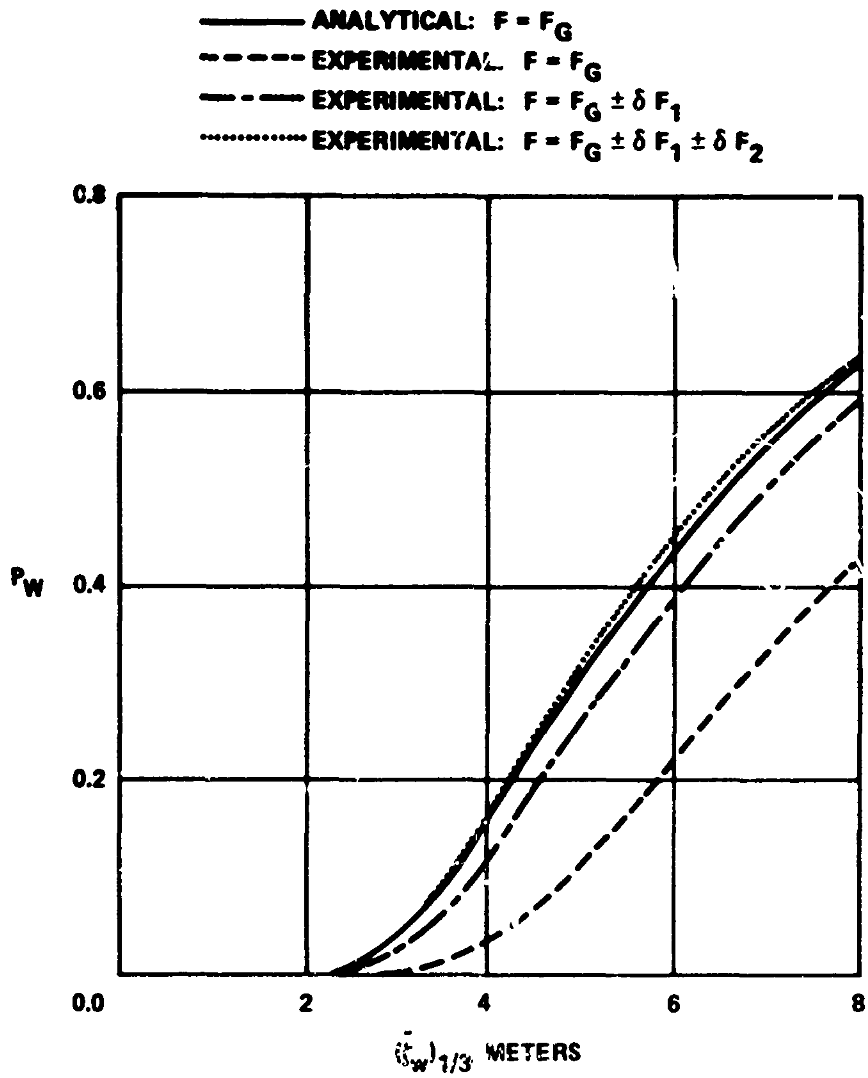
Faired Relative Motion Transfer Functions at After Perpendicular and 12.5 Knots

Figure 19



Significant Single Amplitude of Relative Motion Per Unit Significant Wave Height as a Function of Modal Wave Period at the After Perpendicular and 12.5 Knots

Figure 20



Probability of Deck Wetness at the After Perpendicular and 12.5 Knots for T_0 = 7.26 Seconds, as a Function of Significant Wave Height

Figure 21

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